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(54) Control circuit.

(57) A method of controlling the current flow in the solenoid winding 13 of an electromagnetic actuator in which the current flowing in the winding is controlled by a pair of switches SW_1 and SW_2 connected in series with the ends of the winding and a pair of supply terminals respectively. A pair of flywheel diodes D_1 and D_2 are provided. The switches are both closed to allow the current to rise to a peak value and then one switch is opened to allow the current to decay at a first rate through one diode and then the second switch is opened to allow the current to decay at an increased rate through both diodes. The current is allowed to decay below the normal hold value and then is raised to the hold value.

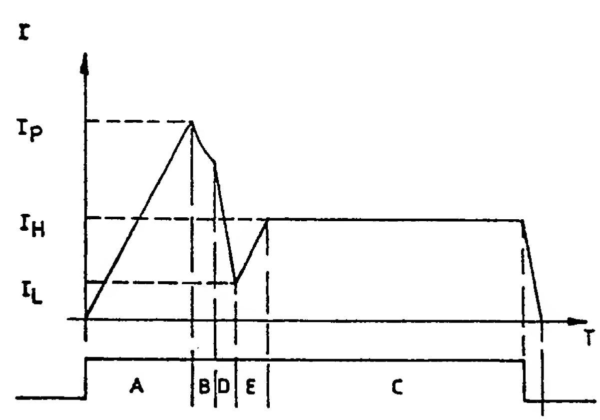

FIG.3.

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CONTROL CIRCUIT

This invention relates to a method of and a control circuit for controlling the flow of current in a solenoid of an electromagnetic actuator having an armature, the armature in use being coupled to a member movable upon energisation of the solenoid, into contact with a stop.

In order to obtain rapid movement of the armature and the member coupled thereto it is conventional pratice to apply a drive voltage to the solenoid which is much higher than that required to hold the armature and in particular the member, in contact with the stop. The high voltage produces a high rate of rise of current in the solenoid which results in a rapid increase in the magnetic flux in the magnetic circuit of the actuator. The usual practice is to allow the current to rise to a peak value following which the solenoid is disconnected from the supply so that the current decays at a relatively low rate due to the provision of a fly wheel diode. When the current reaches a predetermined lower value the solenoid is reconnected to a controlled voltage supply to provide a continuous holding current or alternatively the supply is switched to maintain a mean holding current.

The movement of the armature and the member lags behind the rise in current. This is because a certain value of magnetic flux is required before the armature and member start to move. As the armature starts to move the air gap diminishes and the magnetic pull increases so that even taking into account the inertia of the armature and member the armature and member are accelerated towards the stop. The stop is contacted with considerable velocity which causes a bouncing action to take place. If for example the member is the valve member of a fuel control valve, pressure waves can be set up which may cause cavitation in the fuel besides making it difficult to decide when the valve is effectively closed.

In order to minimise the problem of bounce it has been the practice to minimise the acceleration of the armature and also to provide fluid damping. There is, however, a practical limit to the amount of damping which can be employed and to the reduction of acceleration because both of these result in a reduction in the speed and consistency of operation. It should be noted that whilst the armature and member start to move before the peak value of current is attained the stop will not be engaged until after the current has been allowed to decay and the period of bounce may not be completed until after the lower holding current is flowing in the solenoid.

It has been found that by modifying the current flowing in the solenoid between the attainment of the peak value of current and the switch to the holding current, a substantial improvement in the operation of the actuator is obtained.

According to the invention a method of controlling the flow of current in the solenoid of an actuator comprises connecting the solenoid to a high voltage supply to obtain a rapid rise in the current flowing in the solenoid, disconnecting the solenoid from the supply when a peak value of current flows in the winding, allowing the current in the solenoid to decay at a first rate, increasing the rate of decay of current until the current reaches a value below the hold value of the current and then increasing the current to the hold value.

According to a further feature of the invention a control circuit for controlling the flow of current in the solenoid of an electromagnetic actuator comprises first and second switches for connecting the first and second ends of the solenoid to first and second supply terminals respectively said terminals in use, being connected to a source of electric supply, first and second diodes connected between the first and second ends of the solenoid and the second and first terminals, said diodes being poled so that closure of said first and second switches does not result in current flow through the first and second diodes from the source of supply and control means operable upon receipt of a control signal to initially close said switches to achieve a rapid rise of current in the solenoid until a peak value of current is attained, then opening said first switch to allow the current to decay at a first rate, then opening said second switch to allow the current to decay at an increased rate and then closing at least one of the switches to allow the current flowing in the solenoid to be brought back to a holding value.

In the accompanying drawings:-

Figures 1 and 2 show the current flow and lift diagram of an actuator controlled by a known control method,

Figures 3 and 4 correspond to Figures 1 and 2 but show the diagram obtained when the actuator is controlled in accordance with the invention,

Figure 5 is an electrical control circuit for the actuator,

Figure 6 shows in greater detail part of the control circuit of Figure 5, and

Figure 7 shows a modification of said part of the control circuit.

Figures 1 and 2 illustrate the current and armature lift diagrams of an actuator which is controlled in the conventional manner, the control pulse being indicated at 9. From Figure 1 it will be seen that there is a period A during which the

current I flowing in the solenoid rises at a high rate to a peak current value IP and this is followed by a period B during which the solenoid is disconnected from the supply, in which the current decays. During the period B the current in the winding flows through the usual fly wheel diode. The current is allowed to fall to a hold value IH and when this value is reached the solenoid is reconnected to a supply to maintain either the continuous value of holding current IH or by well known switching techniques, a mean value. The holding current is maintained for a period C and at the end of the period C which occurs when the control pulse 9 is removed, the current decays quickly by reason of a special switching arrangement which will be described. As will be seen from Figure 2 movement of the armature does not start to take place until part way through the period A and it continues in the period B until a stop is engaged and the aforesaid bounce occurs.

Figures 3 and 4 show the equivalent diagrams but for the arrangement where the current is controlled in accordance with the invention. The same periods A, B and C are identified but it will be noted that period B is now shorter and between periods B and C there are two further periods D and E. In period D the current falls at a rate which is higher than in period B and this is achieved by the circuit to be described. The current is allowed to fall to a value IL which is below the holding current IH and in period E the current increases at a high rate conveniently generated by the same voltage as in period A, until the value IH is reached. From Figure 4 it will be seen that the lift curve as the armature approaches the stop is more rounded than in Figure 2, the armature in fact approaches the stop with a reduced velocity. It will be noted that the bounce has been eliminated and although the armature may take fractionally longer to reach the stop the performance of the actuator is more predictable.

Referring now to Figure 5, the circuit includes terminals 10 and 11 for connection to the positive and negative terminals of a source of DC supply 12. The solenoid winding of the actuator is indicated at 13 and one terminal thereof is connected to the supply terminal 11 by way of a switch SW1. The other terminal of the winding is connected through a current sensing device 14 to one terminal of a switch SW2 the other terminal of which is connected to the supply terminal 10. A first diode D1 has its anode connected to the one terminal of the winding and its cathode connected to the supply terminal 10 and a second diode D2 has its anode connected to the supply terminal 11 and its cathode connected to the said other terminal of the winding.

The switches SW1 and SW2 are shown as relay contacts but in practice will be semi-conductor devices the conduction of which is controlled by a control network 15. The network receives a control pulse 9 at an input 16 and it has a further input which receives a signal from the current sensing device 14. The network also controls the operation of a current controller 17 which is shown to be connected in parallel with the switch SW2.

In operation, upon receipt of the control pulse, switches SW1 and SW2 are closed so that the winding 13 is connected directly to the supply terminals. The current in the solenoid rises rapidly and at the end of the period A when the peak current value IP is sensed, switch SW1 is opened and diode D1 acts as a fly wheel diode so that the current in the winding decays at a low rate. At the end of period B switch SW2 is opened and both diodes conduct, the current decaying more quickly and the energy in the winding being returned to the source of supply. At the end of period D both switches are closed and the winding is reconnected to the supply so that the current rises quickly and when at the end of period E the hold value IH of the current is detected, the switch SW2 is opened and the current controller 17 is brought into operation. When the control pulse is removed switch SW1 is opened and the current controller 17 is switched off so that both diodes conduct and the current falls rapidly with the energy recovered from the winding being returned to the source of supply.

It will be understood that the roles of the switches SW1 and SW2 can be reversed but in this case the current controller will be connected in parallel with the switch SW1. As an alternative to a separate current controller 17 the switch with which it would be connected in parallel may be switched ON and OFF to provide a mean holding current. This switch must be a higher quality component than the other switch in view of the more arduous duty it must perform.

In practice it is required to control a plurality of solenoids in turn and Figure 5 shows a further winding 13A the one terminal of which is connected to the supply terminal 11 by way of a switch SW3. A further diode D3 is provided which functions so far as the winding 13A is concerned, in the same way as diode D1 and the switch SW3 has the same role as the switch SW1.

Figure 6 shows one example of the control network 15 and it includes a switch control circuit 18 which has outputs to the aforesaid switches and the current controller 17. It also has an input 19 to determine which of the solenoids in the multi-solenoid arrangement is to be energised. The network also includes a current level detector 20 which receives the signal from the current sensor 14 and two further inputs for setting the peak current IP and the holding current IH. The network

also includes a timer 21. The current level detector 20 provides signals to the control circuit 18 when the peak current IP is attained and the holding current IH. The timer can be responsive to the start of the control pulse or the attainment of the peak current IP. The timer determines periods. Switch SW1 is therefore opened upon the detection of the peak current IP and then the timer will cause opening of switch SW2 for the period D either a predetermined time after the start of the control pulse or a predetermined time after the attainment of the peak current. The set inputs detector 20 and also the timer 21 are shown as being adjustable. In practise they will at least be preset or replaced by fixed value components.

An alternative form of the control network 15 is seen in Figure 7 in which the switch control circuit 18 is controlled by a more complex form of level detector 22 in which the peak value IP, the hold value IH and the desired current levels at the end of periods B and D are preset.

If the graphs of Figures 1 and 3 are compared it will be seen that whilst the peak current IP is substantially the same the holding current IH in Figure 3 is reduced. This is because with the reduction or elimination of bounce, the holding force as determined by the holding current can be reduced. If desired the peak current IP can be increased in order to achieve more rapid movement of the armature. With the usual arrangement this would increase the possibility of bounce but with the control method described the bounce will be minimised. If necessary the holding current IH can be increased to provide an increased force to control the armature. This is possible because the holding current level is reached only when the armature is close to its stop. The armature does not therefore undergo any significant acceleration and the high holding force tends to latch the armature against its stop.

It will be understood that in the example of Figure 7 current sensing alone is utilized to control the operation of the switch control circuit. In the example of Figure 6 a timer is used to control periods B and D but this control could be effected by current sensing. Moreover, the periods A and E can be determined using a timer.

Claims

1. A method of controlling the flow of electric current in the solenoid winding (13) of an actuator comprising connecting the solenoid winding to a high voltage supply (12) to obtain a rapid rise in the current flowing in the solenoid winding, disconnecting the solenoid winding from the source of supply when a peak value of current flows in the winding, allowing the current in the solenoid winding (13) to decay and reconnecting the solenoid winding to an electric supply to maintain a hold value of current in the solenoid winding, the current is initially allowed to decay at a first rate and then at a second rate which is greater than the first rate, the current in the solenoid winding being allowed to fall below the hold value before the solenoid winding is reconnected to a supply to maintain the hold value of the current.

2. A control circuit for controlling the flow of electric current in the solenoid winding (13) of an electromagnetic actuator, the circuit comprising first and second switches operable to connect the winding to a source of electric supply (12), and control means (15) for controlling the operation of said switches, said first and second switches (SW1, SW2) connecting the first and second ends of the solenoid winding (13) to first and second electric supply terminals (11, 10) respectively, the circuit further including first and second diodes (D1, D2) connected between the first and second ends of the solenoid winding and the second and first electric supply terminals (10, 11) respectively, said diodes being poled so that closure of the first and second switches (SW1, SW2) does not result in current flow through the diodes from the supply terminals, said control means (15) upon receipt of a control signal (9), acting to close said switches (SW1, SW2) to achieve a rapid rise of current in the solenoid winding (13) until a peak value (IP) in attained, then acting to open said first switch (SW1) to allow the current to decay at a first rate, then acting to open said second switch (SW2) to allow the current to decay at an increased rate and then closing at least one of the switches, to allow the current flowing in the solenoid winding (13) to be brought back to a holding value (IH).

3. A control circuit according in Claim 2 in which said control means (15) closes the first switch (SW1) and effects periodic closure of the second switch (SW2) to bring the current in the solenoid winding (13) to the holding value (IH).

4. A control circuit according to Claim 2 in which said control means (15) closes the first switch (SW1) and causes operation of a current controller (17) connected in parallel with the second switch (SW2).

5. A control circuit according to Claim 2 including sensing means (14) for sensing the current flowing in the solenoid winding (14), said control means (15) comprises a switch control circuit (18) having outputs to the switches (SW1, SW2), a current level detector (20) responsive to the signal providing by said means (14) said detector (20) providing outputs respectively to said switch control circuit (18) on the attainment of the peak value (IP) and the holding value (IH) of the current.

6. A control circuit according to Claim 5 in which said current level detector (22) provides outputs respectively to said switch control circuit (18) on the attainment of the desired current values at the end of the periods during which the current in the solenoid winding (13) decays at the first rate and the increased rate.

7. A control circuit according to Claim 5 in which the control circuit (18) includes a timer (21) which determines the period during which the current flowing in the solenoid winding (13) decays at said increased rate.

8. A control circuit according to Claim 2 in which said control means (15) includes a timer operable to determine periods A, B, D and E.

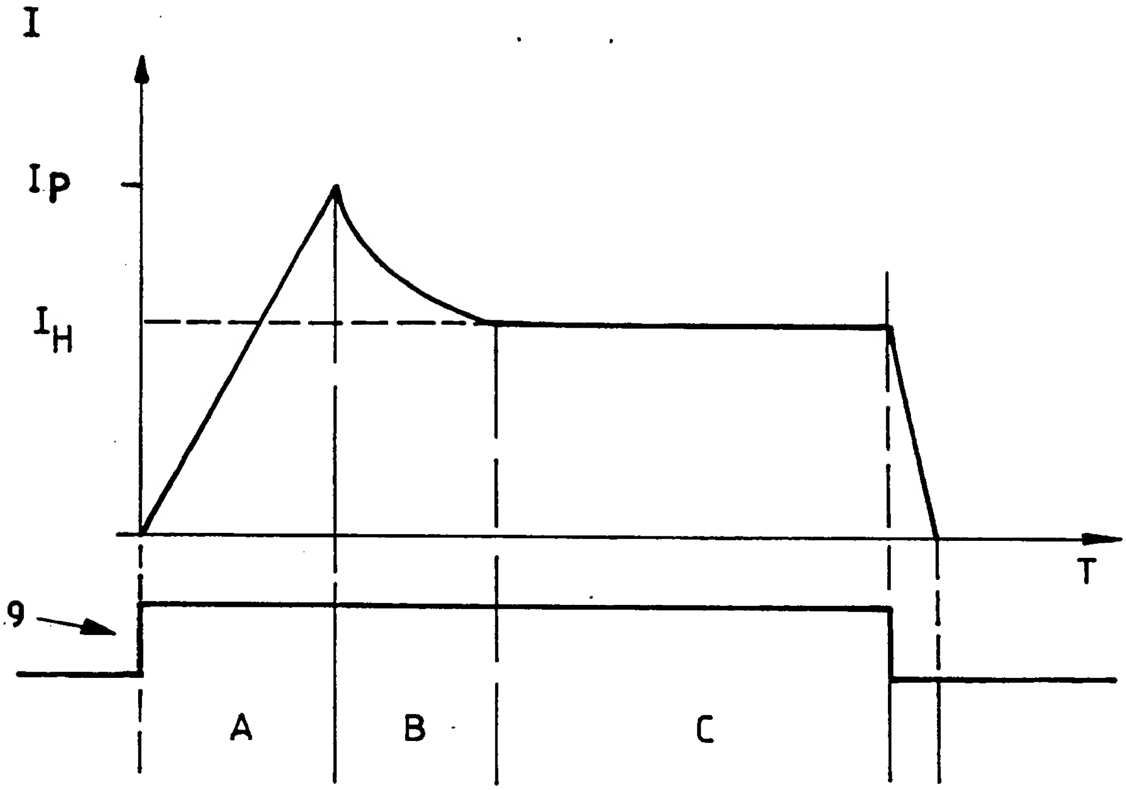

FIG.1.

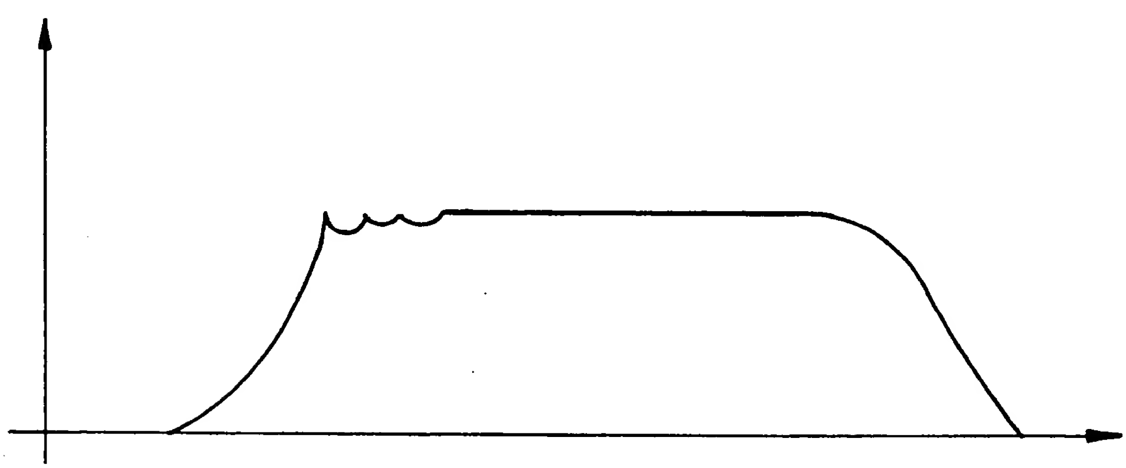

FIG.2.

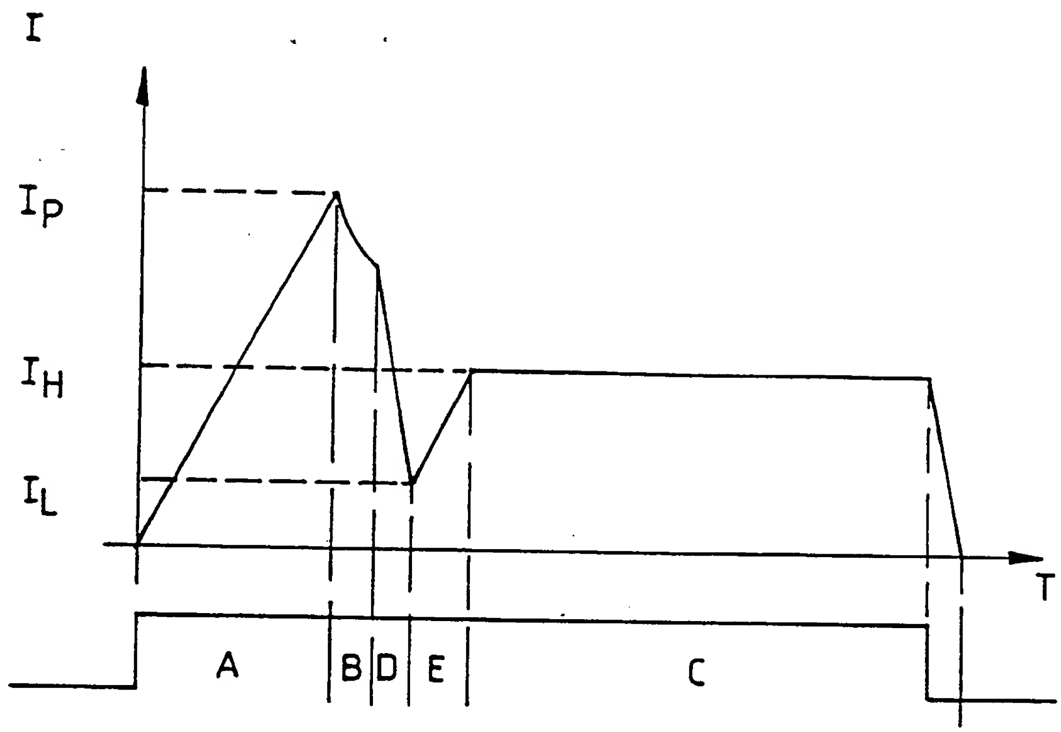

FIG.3.

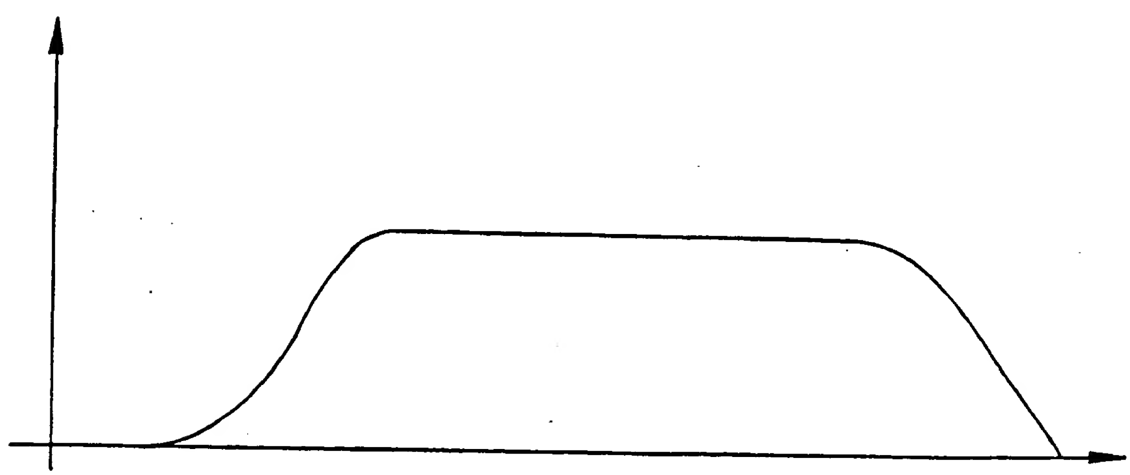

FIG.4.

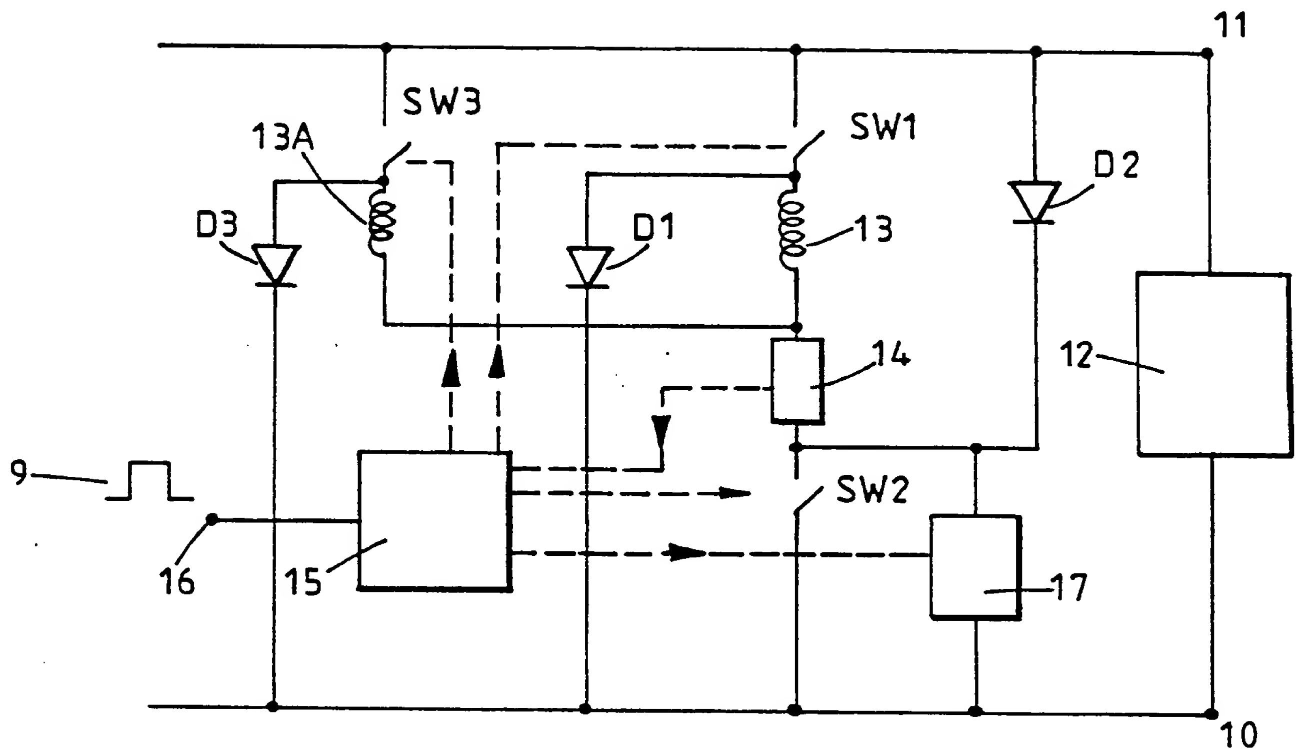

FIG.5.

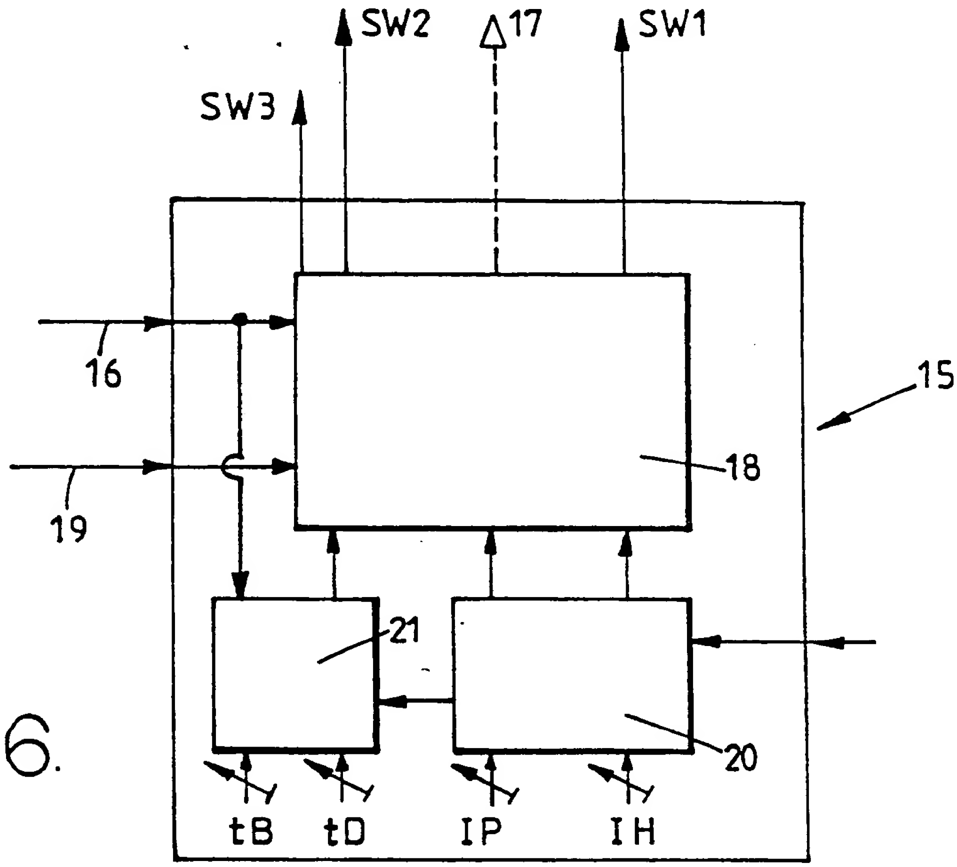
SW2
17
SW1
SW3
16
19
15
18
21
20
tB
tD
IP
IH

FIG. 6.

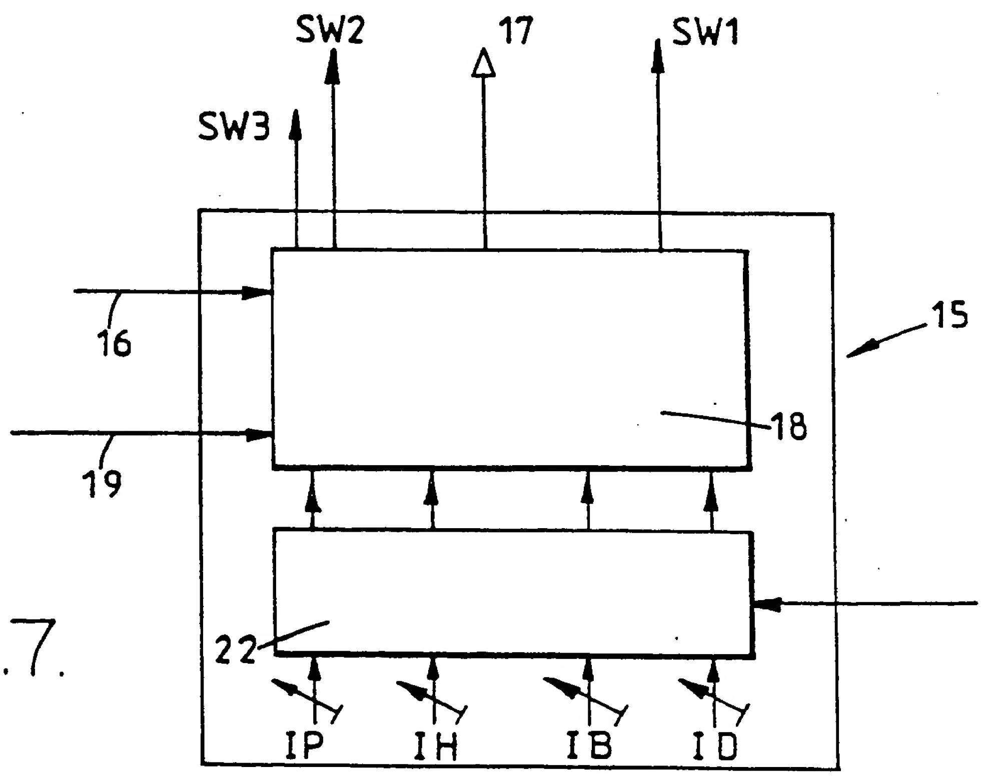
SW2
17
SW1
SW3
16
19
15
18
22
IP
IH
IB
ID

FIG. 7.

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EUROPEAN SEARCH REPORT

Application Number

EP 89 31 2438

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	US-A-3 706 011 (VINCENT) * Column 1, lines 12,13,64-72; column 2, line 58 - column 3, line 1; column 3, line 21 - column 4, line 10; column 4, lines 33-47; figure *	1	H 01 H 47/04 H 01 F 7/18
Y		2-8	
Y	EP-A-0 180 060 (IBM) * Column 3, line 30 - column 4, line 9; column 4, lines 35-40; figures 5,6 *	2,4-8	
A		1	
Y	US-A-4 520 420 (ARIYOSHI) * Column 3, line 32 - column 4, line 21; figures 1b, 2 *	3	
A		1,2,5	

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

H 01 H
H 01 F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	12-03-1990	SALM R.J.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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